Ultra Lightweight Space Optics Challenge Workshop

Applications of Carbon Fiber Composites to Ultralightweight Space Mirrors

Dr. Brian Catanzaro, Mr. David Crowe, Mr. Eldon Kasl
1.1.1.1 Composite Optics, Incorporated

Email: bcatanzaro@coi-world.com
Phone: 619-621-7358/Fax: 619-621-5770
9617 Distrubution Ave, San Diego, CA 92121

Abstract

In order to meet the goals for NASA's Origins Program, 20-40 meter class telescopes require deployable mirrors that are low mass, low thermal distortion, space qualified, and meet the optical requirements for infrared and visible imaging systems. Carbon fiber composites have been used in applications that are traceable to the demands of large aperture telescopes. These include furlable reflectors, solar concentrators, and composite optical mirror surfaces. A review of these applications and the fabrication technology is presented. The critical technologies that must be developed to meet NASA's goals are also be outlined.

1. Introduction

1.2 NASA Goals for Ultralightweight Optics

NASA has communicated a series of goals for optical systems over the next 10 to 20 years. The goals are based on NASA's desire to detect distant and faint objects at visible wavelengths: the imaging of planets in nearby galaxies. Although these goals for these systems are more aggressive, there is little expected change in the payload capacity (mass and size) of launch vehicles. As a consequence, larger optical systems are expected to fit in the current launch vehicles and deploy. The system level requirements can be expressed succinctly as increased aperture size, visible wavelength performance, and reduced areal density.

These system level requirements impact the technology development of mirrors for these optical systems. Increased aperture size implies 5 m to 30 m apertures. These may be filled apertures or sparse apertures. The visible imaging requirements imply $\lambda/20$ (RMS) surface figure where the reference wavelength is 0.6328 µm. The surface roughness requirement is 20 Å (RMS). The progression of areal density requirements has been summarized in a graph supplied by Marshall Space Flight Center (see Figure 1.1). In this graph, several mirrors and systems are shown. At 250 kg/m^2 is the Hubble Space Telescope. At 35 kg/m^2 is the ALOT system. Shown at 15 kg/m^2 are the NMSD and AMSD programs that are developing mirrors for the Next Generation Space Telescope (NGST). Farther out, in 2010, is the goal of generating mirrors that are 5 kg/m^2. The technology for achieving this areal density has not been clearly identified.

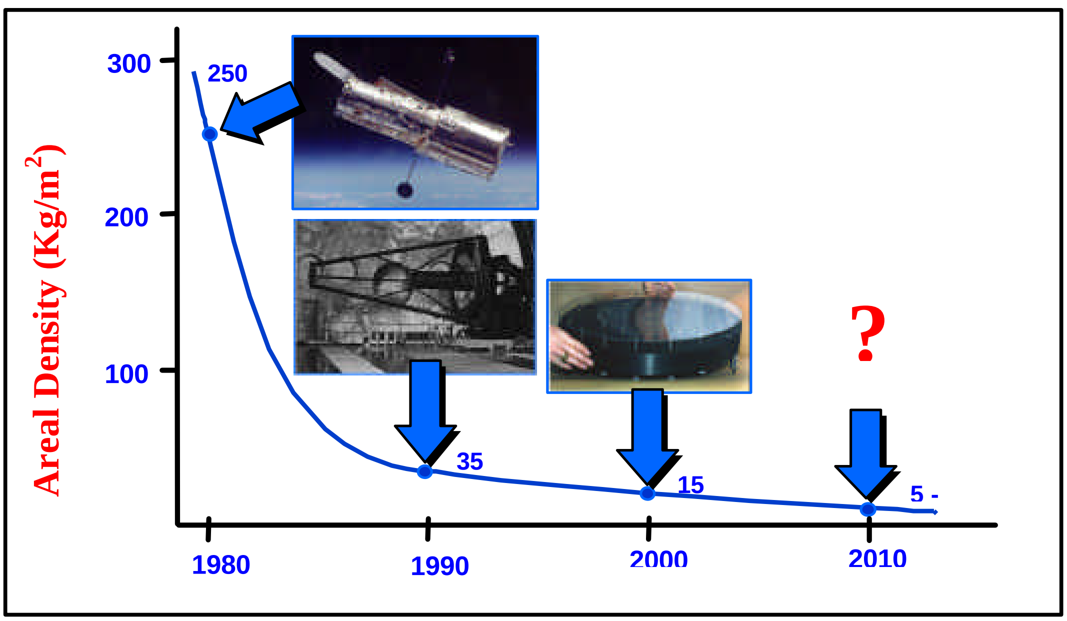

Figure 1.1: Trends in Areal Density

1.3 Carbon Fiber Composite Materials

Carbon fiber composite materials (composites) play a significant role in lightweight mirror development. Carbon fiber composites are fibers supported in a resin matrix. The materials have unique properties along the direction of the fibers. In the direction perpendicular to the fibers, the composite is dominated by the properties of the resin. Composite materials are not traditional mirror substrate materials. However, a brief survey of the properties of mirror materials and a comparison between these materials and composites shows why these materials are relevant. Table 1.1 is a comparison of intrinsic and derived properties of several common mirror materials in comparison with composites.

Table 1.1: Comparison of Mirror Substrate Materials

	r Density kg/m^3	E Young's Gpa	a CTE ppm/K	K Thermal Cond. W/m-K	sqrt(E/r) Freq for same Geom	a /K S State
Pyrex	2230	63	3.300	1.13	1.06	21.676
ULE	2210	67	0.030	1.31	1.10	0.170
CFC	1780	93	0.050	35.00	1.44	0.004
Aluminum	2700	68	22.500	167.00	1.00	1.000
MMC	2910	117	12.400	123.00	1.26	0.748
Beryllium	1850	287	11.300	216.00	2.48	0.388
SiC	3210	465	2.400	198.00	2.40	0.090

The intrinsic properties to the materials are density (ρ), Young's modulus (E), coefficient of thermal expansion (α), and thermal conductivity (K). Density is relevant because it drives mirror weight or areal density and hence the ability to launch a space borne mirror; typically the lower, the better. Young's modulus plays a critical role in determining the mirror stiffness. This is critical in determining the fundamental frequency of a mirror substrate and its interaction with sources of vibration (slewing, pointing, reaction wheels, gyros); higher values are preferred. The coefficient of thermal expansion is key to mirrors that must survive the cryogenic environment of space without significant mirror deformation; a lower value is preferred. Thermal conductivity is important because it allows the transfer of heat away from heat sources and will allow the mirror to reach a steady state faster; higher values are better.

Two derived properties are summarized: specific stiffness and a steady state heat transfer coefficient. The specific stiffness compares stiffness and weight. This property is an expression of structural efficiency. Materials that are not stiff and are heavy do not have a high fundamental frequency; higher values of specific stiffness are preferred. The steady state heat transfer coefficient is an expression of the effect of heat on the substrate. Mirrors with high heat conductivity and low thermal expansion will equilibrate quickly and in the presence of thermal gradients, will distort very little; a lower value is preferred. As seen in this table, composite materials offer a significant advantage in specific stiffness and the steady state heat transfer coefficient.

It is worth noting that composite substrates are manufactured in a method that is significantly different from standard mirror materials. Materials such as glass, ceramics, and metals are melted, crystallized, or cast. Later the substrates are machined to remove unwanted material. Finally, they are polished to implement a smooth, optical figure. Composite materials are created in an additive fashion. Thin compliant layers (plies) of material are arranged in a specific configuration. The material is then hardened during a curing process. It is cut, assembled, and bonded together. Only the material necessary to form the mirror are used. There is little need to remove excess material by machining the substrate. Traditional and non-traditional methods are used to create the mirror surface.

2 Classification of Substrate Designs

2.1 Classical Lightweighting

Designs for lightweighting mirrors can be categorized into four groups: contoured back, open back, sandwich mirrors, and deformable mirrors. Each of the designs comes with features that allow for various mass savings and compromises in stiffness.

Open back mirrors have been a very popular design for lightweighting. Using advanced machining techniques, large amounts of material can be removed from the backside of the mirror. This leaves the impression of a thin mirror surface supported by a series of walls or ribs. Care must be taken in the design to ensure that the appropriate stiffness can be maintained when the mirror is extremely lightweighted.

Sandwich style mirrors utilize contiguous mirror surface (facesheet), a sparsely supported center section, and a contiguous mirror back (backsheet). This design offers a high degree of lightweighting without significant compromises in stiffness. However, fabricating this type of structure is extremely challenging. Standard machining techniques do not accommodate this type of design. Some mirrors have been fabricated by fusing a backsheet and facesheet to a core

Contoured back mirrors are the simplest form of lightweighting. Unnecessary mass is removed from the outer perimeter of the mirror by machining a gradual thickness variation in the backside of the substrate prior to optical figuring. This technique may be used to form a single or double arch. Typically the thickest point of the double arch forms an annulus at the optimum support point for 1 g loading: close to 70% of the radius of the mirror. Stiffness is not greatly compromised using this approach. However, weight savings is moderate.

One method of increasing the amount of lightweighting in a design is to accommodate surface figure compensation with actuators. A thin meniscus can be fabricated for the mirror surface and mounted to actuators. The actuators, in turn, are mounted to a reaction structure in order to provide a rigid structure to “push” against.

In the extreme of this technique, there are many actuators and an extremely thin facesheet with a lightweight reaction structure. One drawback of this extreme is the weight of the actuators and associated fittings and cables. Another disadvantage is the complexity in wavefront sensing and control algorithms necessary to measure the aberrations generated by the mirror surface and correct for them.

A deformable mirror can be engineered with fewer actuators and a more rigid mirror surface. This can be classified as a semi-rigid mirror. Using this approach, lower order aberrations can be corrected with a few actuators with very little additional weight.

2.2 Lightweight Composite Mirrors

Composite mirrors benefit greatly from symmetry in the design. Whenever possible, the mirror should be symmetric about a surface that is parallel to the front and back surfaces. The advantage of this approach is most apparent when considering the construction of composite materials. Since the composite material consists of macroscopic fibers oriented in various layers, it is important to balance the opposing forces of the fiber and the resin. Symmetry of design achieves this property while relaxing the manufacturing tolerances on the composite materials. If symmetry is not obeyed in a design, more care must be taken to guaranteeing material properties prior to fabrication. Given this caveat, composite mirrors can still be classified in the same manner as classical lightweight mirrors.

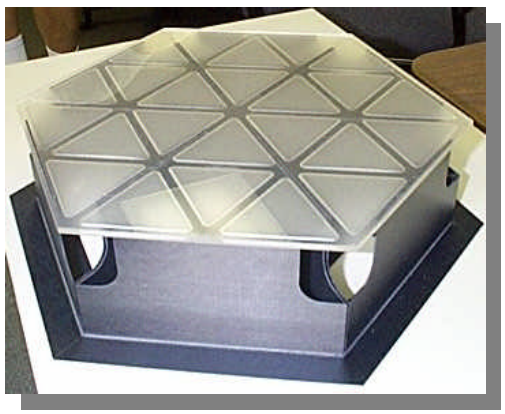

Figure 2.1: Open Back Hybrid Composite Mirror Fabricated by COI

Open back mirrors are common by virtue of the ease of construction. An example of this is the 300 mm diameter mirror shown in Figure 2.1. This mirror is a hybrid. It utilizes a glass facesheet and ribs to support the thin facesheet. The back is open to further lightweight the mirror. Material selection and qualification was key to ensuring a stable mirror given the degree of asymmetry in the design.

Sandwich style mirrors have been fabricated using a number of core geometry. Variations include composite or glass facesheets and backsheets, isogrid, eggcrate, and radially symmetric core designs.

The aforementioned issue of symmetry is the primary reason that contour back mirrors are rarely implemented in composites. Composites are typically not machined with contours to the surface. This would interrupt the fibers that reinforce the substrate and cause large asymmetry and instability.

Deformable mirrors have been fabricated using composite materials. Large radio frequency reflectors have been fabricated with adjustments that allow for figure control. Reaction structures that support actuators that deform surfaces of glass have been fabricated.

2.3 Trends in Lightweighting Composite Mirrors

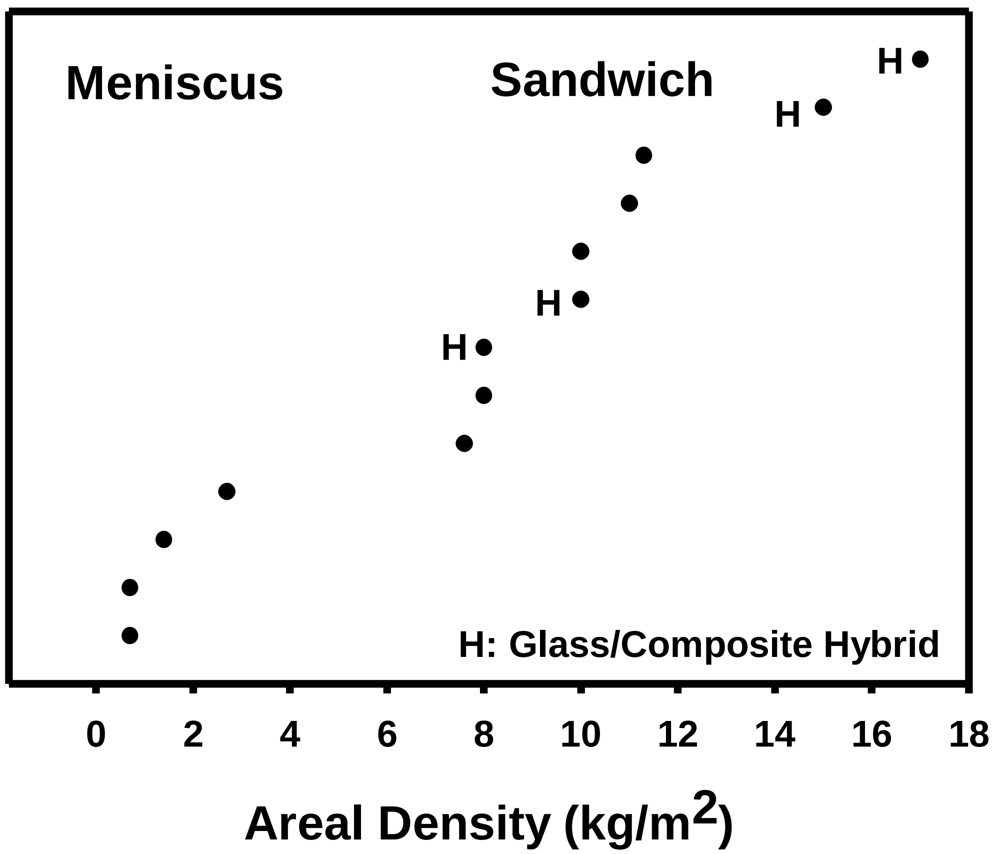

Figure 2.2: Areal Density as a Function of COI Mirror Designs

The trends in lightweight mirrors can be characterized by examining the areal density as a function of the type of mirror. Sandwich mirrors and open back mirrors tend to be in the 7 kg/m^2 class or above. Meniscus (or thin membrane) composite mirrors have demonstrated areal densities less than 1 kg/m^2. Typically, the addition of glass to the sandwich or open back design will limit the areal density to 8 kg/m^2 or above. The limit in areal density is often determined by the thickness of glass required for the optical fabrication technique rather than the stiffness requirement. Meniscus designs are the only designs that appear to achieve the ultralightweight goals expressed by NASA.

2.4 Concepts for Ultralighweight Deployable Composite Mirrors

Concepts for deployable composite mirror technology have been inspired by microwave reflector technology. Three such implementations are rollable, iris, and umbrella. All three of these technologies have been demonstrated at the 1-2 kg/m^2 areal density for reflectors. These three design concepts serve as starting points for ultralightweight composite mirror deployment.

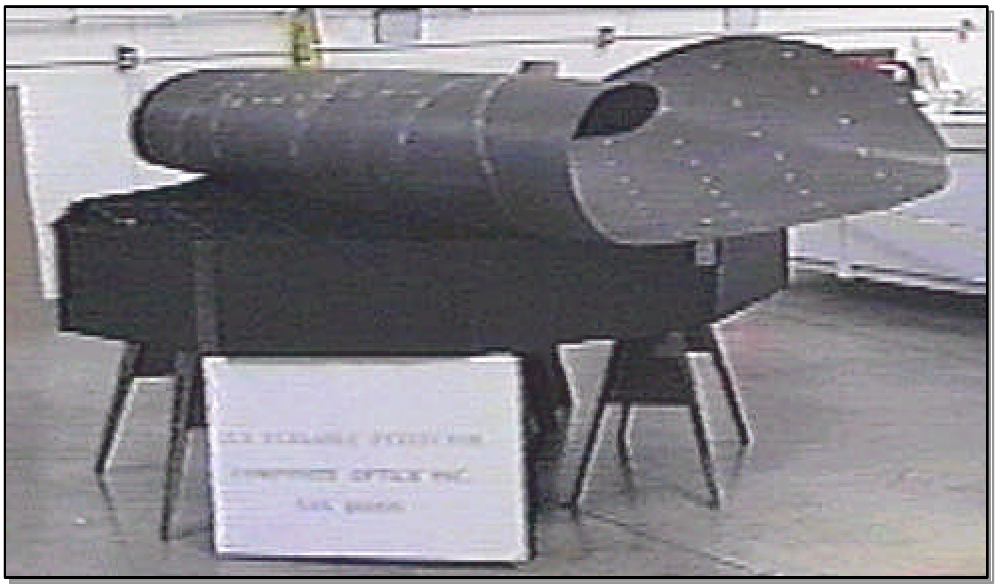

Figure 2.3: 3.3 m Furlable Reflector (COI)

The rollable or furlable technology for mirror deployment was first demonstrated and patented by COI in the early 1990's. A 3.3 m parabolic meniscus reflector was fabricated (see Figure 2.3). The deployment mechanism was to roll the reflector into a tube shape. The shape was held by fastened cord. When the fastener was released, the energy stored by rolling a meniscus allowed the membrane to unfurl onto a support structure. The location of the meniscus on its support structure was ensured by using a series of small magnets and metal strips.

The iris technology was demonstrated on a 1 m parabola. A parabola was segmented into a series of shapes similar to the iris of a photographic camera. However, instead of deploying from a plane with a large hole to a plane with a small hole as a camera iris does, the composite parabola deployed from a cylinder to a parabola (see Figure 2.4).

Figure 2.4: Iris Deployable Reflector (COI)

A third concept is based on an umbrella mesh antenna developed by Harris Corporation. The mesh antenna utilizes a series of tension wires and support rods to expand a 10 m class diameter mesh reflector. A variation of this concept is being developed for an optical reflector to supply solar energy to a transport vehicle (Solar Orbit Transfer Vehicle). In this implementation, the tension wires extend like an umbrella to deploy a series of optical reflectors made of thin meniscus composite material. For the Solar Orbit Transfer Vehicle, both an inflatable and umbrella version of a deployable 2 m class reflector were compared. For this application, the mass estimates for both the inflatable and composite version were the same.

3 Techniques for Optical Fabrication

Composite mirrors require some unique methods of optical fabrication.

3.1 Surface Roughness

Surface roughness or micro roughness refers to variations in the surface of the mirror at a very fine scale. Usually measurements are taken over the micron to millimeter range over the surface and a profile of the depth is generated.

Producing a smooth surface is relatively easy using composite mirror materials. Often this surface can be created during the curing process with by using an optically polished glass layup tool. In addition, materials such as metals (films or plating) or epoxies can be applied after the composite has cured. When these materials are used in conjunction with polishing, diamond turning, or replication it is relatively straightforward to achieve 10–20 Å (RMS) surface roughness. This has been demonstrated in a number of prototypes ranging from far infrared reflectors (FIRST mirror prototype) to afocal radiators (thermal radiators for rejecting thermal energy from a satellite). Using these processes, the goals for surface roughness for ultralightweight space optics can be met.

3.2 Surface Figuring

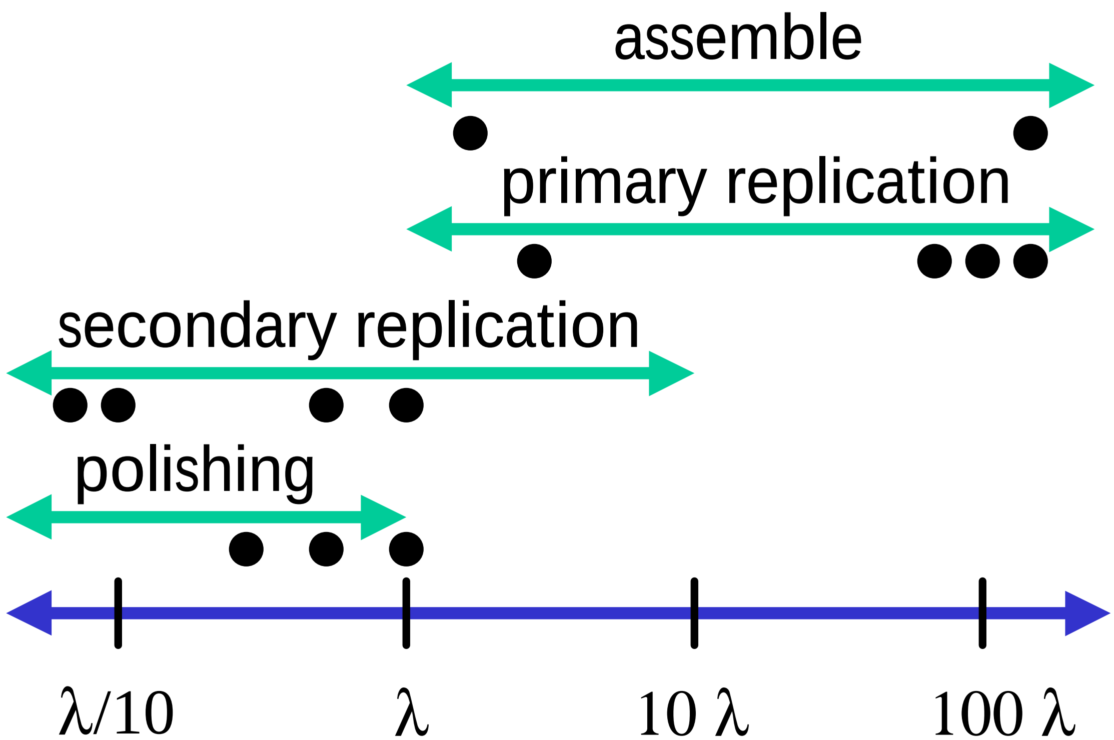

Figure 3.1: Comparison of the Surface Figure Accuracy of Various Techniques in Composite Mirrors. Data Points Indicate Actual Mirrors Fabricated and Measured.

Surface figure is the match between the desired surface and the manufacture surface over a macroscopic scale. Techniques that have been used to fabricate an optical surface in a composite mirror include: primary replication, secondary replication, assembly, polishing, and ion figuring. The surface figure accuracy of these techniques is depicted in Figure 3.1.

Primary replication refers to producing an optical figure directly from the composite layup mold. Secondary replication uses a coarsely figured, cured composite. After the composite is fabricated, a second, optically polished mold is prepared. An optical coating is applied to the second mold. The coating is then bonded to the composite with an adhesive or resin which fills the gaps between the coarsely figured composite and the second tool. After curing, the composite, adhesive, and optical coating are then lifted off of the second tool.

Composite mirrors have been assembled using composite backup structures and optically polished or replicated facesheets. Assembly has been completed with the assistance of an optically polished assembly tool. Typically the facesheet is held by a vacuum to the assembly tool while the backup structure is bonded to the facesheet.

Composite mirrors have been coated with a variety of materials (glass, epoxy, metals) and polished later. The polishing has been in the form of continuous planetary polishing and small tool polishing. Ion figuring has also been used. Its advantage is that this technique is a zero force removal of material.

3.3 Challenges in Ultralightweight Composite Optics

The most significant challenge to producing ultralightweight composite optics is in optically figuring meniscus mirrors. As discussed previously, meniscus mirrors show the most promise for ultralightweight (1-2 kg/m^2). However, it is difficult to achieve visible imaging quality surfaces (λ/20 RMS) over large areas. The most common form of figuring meniscus mirrors is either primary or secondary replication.

Glass mirror fabricators are concerned with the force applied by polishing and the resulting quilting in the surface figure. Due to the thin design of meniscus mirrors (0.040”), composite mirror manufacturers are concerned with internal stresses. Internal stresses resulting bending either during replication or upon exposing the mirror to thermal changes.

Internal stresses can be caused by a number of phenomena. Variations in resin and fiber properties can cause stresses. Variations in ply angles can cause internal stresses upon curing or cycling the mirror over a temperature range. Stresses can also be built up during secondary replication. In this process, materials are added to the composite substrate after fabrication. If the materials are added with a non-uniform thickness, this can lead to internals stresses. If materials are only added to one side of the meniscus, then a bimetallic effect may occur when the mirror is exposed to temperature variations, causing internal stresses.

4 Critical Technologies to Meet Ultralightweight Goals

The critical technologies for ultralightweight composite mirrors fall into four categories: coatings, molds, material control, and actuation.

For extremely large scale mirrors (>5 m), optical coatings must be developed that are robust to deployment. Whether the deployment is by furling, iris, or umbrella techniques, it is likely to be damaged by contact during stowage. The coatings will also need to be extremely elastic in order to stow in a compressed form and then expand to deployed form without delaminating, flaking, or cracking. These coatings must be tested over a significant lifetime to demonstrate that stowage for 5 to 10 years is feasible.

Given that replication (primary and secondary) is the most likely technique for fabrication of ultralightweight composite mirrors, mold technology is critical to success. Molds will be required to shape the original composite shape as well as the optical figuring. These molds should be commensurate in size with the end use mirror segment. They must be polished and measured to optical accuracy ensure accurate replicas. This may limit the maximum aperture size of individual segments of composite mirrors.

As discussed earlier, material uniformity and control is essential to avoiding internal stresses. This includes fiber and resin control as well as uniformity during the layup process.

Finally, lightweight actuation may ultimately play an important role in achieving highly accurate figure. The actuators must be lightweight and integral to the structure (< 0.5 kg/m^2). The interconnect of wires that carries signals to the actuators should likewise be lightweight and integral to the structure (< 0.1 kg/m^2). They actuation process must be accurate to fractions of a wave ($\lambda/100$). However, the bandwidth need not be high. Given the dynamic environment and long observation times, it is likely that actuator updates by much less than 1 Hz.

5 Conclusion

The goals for ultralightweight optics were described. No technology for mirror fabrication has clearly achieved all of these goals. With development, composite mirror technology shows promise of meeting these goals. The most effective design appears to be thin meniscus sheets of carbon fiber composite. Current techniques appear to meet surface roughness requirements. The most likely candidate for surface figuring of these mirrors is primary or secondary replication. Using this technique, surface figure requirements are currently out of reach. However, by applying effort to a series of critical technologies, significant improvements can be realized.